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Chandra/HETGS Spectroscopy of the Anomalous X-ray Pulsar 4U 0142+61

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Abstract. We report on a 25 ks observation of the anomalous X-ray pulsar 4U 0142+61 with the High Energy Transmission Grating Spectrometer (HETGS) on the *Chandra X-ray Observatory*. The continuum spectrum is consistent with previous measurements and is well fit by an absorbed power-law + blackbody model with photon index $\Gamma = 3.3 \pm 0.4$ and blackbody temperature $kT = 0.418 \pm 0.013$ keV. The pulsar frequency was 0.1150966±0.0000017 Hz and the pulse fractions were between 8.7% and 21%, which are also consistent with past measurements. No evidence was found for emission or absorption lines with an upper limit of ≈50 eV on the equivalent width of a broad feature in the 2.5–13 Å (0.95–4.96 keV) range. The absence of a proton cyclotron line strongly constrains magnetar atmosphere models and hence the magnetic field strength of the neutron star. For the energy range given above, the allowed magnetic field strengths of 4U 0142+61 are $B < 1.9 \times 10^{14}$ G and $B > 9.8 \times 10^{14}$ G.

1. Introduction

Anomalous X-ray pulsars (AXPs) were suggested as a class by Mereghetti & Stella (1995) based on their observational properties. AXPs have a tight range of spin periods, 6–12 s, luminosities of order 10^{34}–10^{35} erg s^{-1}, and a soft X-ray spectrum described by a blackbody of temperature 0.2–0.6 keV and a power-law of index 2–4 (see, Gavriil & Kaspi 2001, and references therein). These sources also undergo relatively steady spin-down, have faint or unidentified optical counterparts, and have no evidence of orbital motion. The properties of AXPs do not point to a single explanation of the systems, but rather several different models have been suggested to account for the observational properties. These models fall into two general categories: (1) accretion models where the material is from either a very low-mass companion or from a fallback disk (see, e.g., van Paradijs, Taam, & van den Heuvel 1995), and (2) magnetar models which suggest that AXPs are ultra-magnetized (B≈10^{14}–10^{15}), isolated neutron stars (see, e.g., Thompson & Duncan 1996). Recently, atmospheric modeling of magnetars predict that a broad ($\Delta E/E \approx 1$) proton cyclotron absorption line should be apparent in the X-ray spectrum of magnetars (Ho & Lai 2001; Zane et al. 2001). High-resolution X-ray spectroscopy should be able to identify the

proton cyclotron feature or at least place limits on the magnetic field strengths of the AXPs.

4U 0142+61 is a member of this class, with spin period of 8.7 s (e.g., Gavriil & Kaspi 2001). X-ray spectra obtained with *ASCA* and *BeppoSAX* were well fitted by a two component model of a 0.4 keV blackbody and a $\Gamma \approx 3.7$ power-law (White et al. 1996; Israel et al. 1999; Paul et al. 2000). Recently, Hulleman, van Kerkwijk, & Kulkarni (2000) identified an optical counterpart based on the *Einstein* position.

2. Chandra/HETGS Results

We observed 4U 0142+61 with *Chandra* on 2001 May 23 for 25 ks using the High Energy Transmission Grating Spectrometer (HETGS; Canizares et al. 2001, in preparation) and the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2001, in preparation). Traditionally, the source has been fit with a power-law and a blackbody both absorbed by neutral gas in the interstellar medium. The results of the *Chandra* fit, shown in Figure 1, are consistent with previous observations of 4U 0142+61. The best fit parameter values are: photon index $\Gamma = 3.3 \pm 0.4$, power-law normalization at 1 keV $A_1 = 0.10 \pm 0.05$ photons keV^{-1} cm^{-2} s^{-1}, blackbody temperature $kT = 0.418 \pm 0.013$ keV and blackbody radius $R_{\rm bb} = (2.0 \pm 0.2) d_{\rm kpc}$ km.

With a well determined continuum model, we then looked for absorption and emission features in the high-resolution spectrum. We fit Gaussian models to the fractional residuals ([data-model]/model) from the continuum fit. The central energies and widths of the Gaussian components were fixed, while the normalizations were fitted. To look for features that had been predicted in the magnetar models (Ho & Lai 2001; Zane et al. 2001), the sigma of the Gaussian was chosen to vary with energy ($\sigma = 0.1 \times E$). The Gaussian model was fit to the data centering at every wavelength point. We were able to determine the best fit amplitude and standard deviation of this result as well as the significance of each feature. There were no features with a significance greater than 4σ. Magnetar models predict equivalent width values of 0.70–0.75E which are significantly above our upper limits of $\approx$50 eV. Thus, there are no features that could be attributed to a proton cyclotron feature in the range 2.5–13 Å (0.95–4.96 keV). For a more detailed account of our analysis, see Juett et al. (2001).

Our timing analysis used the dispersed events identified at the first and second orders. The event arrival times were barycentered and randomized within the frame time of 1.84 s. A lightcurve was created with 2 s bins, from which a power spectrum was made. The power spectrum showed both the fundamental and the second harmonic of the 8.7 s period. The best fit frequency of 0.1150966±0.0000017 Hz was measured from the second harmonic and is consistent with the ephemeris of Gavriil & Kaspi (2001) derived from long term monitoring with *RXTE*. To look at the pulse profile as a function of energy, the events were filtered into five energy bands using the energy column of the event file. The lightcurves for each energy band were then folded on the best fit period and the pulse fraction was determined, defined as PF=$(F_{max} - F_{min})/(F_{max} + F_{min})$ (see Fig. 2). An energy-independent pulsed fraction is excluded at the 1.7σ level.

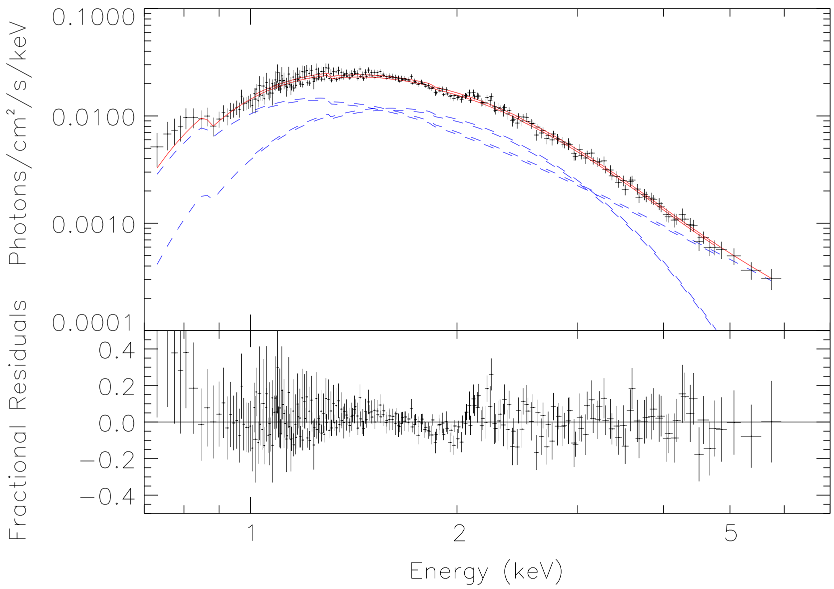

Figure 1. (upper panel) Unfolded energy spectrum of 4U 0142+61 fit with a power-law and a blackbody model. The contributions of the power-law and blackbody components are also shown. (lower panel) Fractional residuals ([data-model]/model) from the power-law and blackbody fit.

3. Discussion

The *Chandra* spectrum of 4U 0142+61 is well fit by a two component power-law and blackbody model absorbed by the interstellar medium, which is consistent with previous observations of the source (White et al. 1996; Israel et al. 1999; Paul et al. 2000). The position we obtained from the *Chandra*/HETGS 0th order confirms the optical identification. No significant features were found in a search of the high-resolution spectrum. We can place a very conservative limit on the equivalent width of any broad feature of ≈50 eV in the range 2.5–13 Å (0.95–4.96 keV). The limits on the equivalent width of any absorption features place strong constraints on the neutron star atmosphere models. Atmosphere models of highly magnetized neutron stars indicate that proton cyclotron absorption would produce a broad feature at an energy $E_B = 0.63 y_g (B/10^{14}\,\mathrm{G})$ keV, where $y_g = (1 - 2GM/c^2R)^{1/2}$ is the gravitational redshift factor (Ho & Lai 2001; Zane et al. 2001). For the range we can reasonably study, 0.95–4.96 keV, our equivalent width limits are much lower than the predicted equivalent widths of order 0.70–0.75E_B. If we assume that the gravitational redshift to the surface is 0.2, then the range of disallowed magnetic field strengths is (1.9–9.8)$\times 10^{14}$ G.

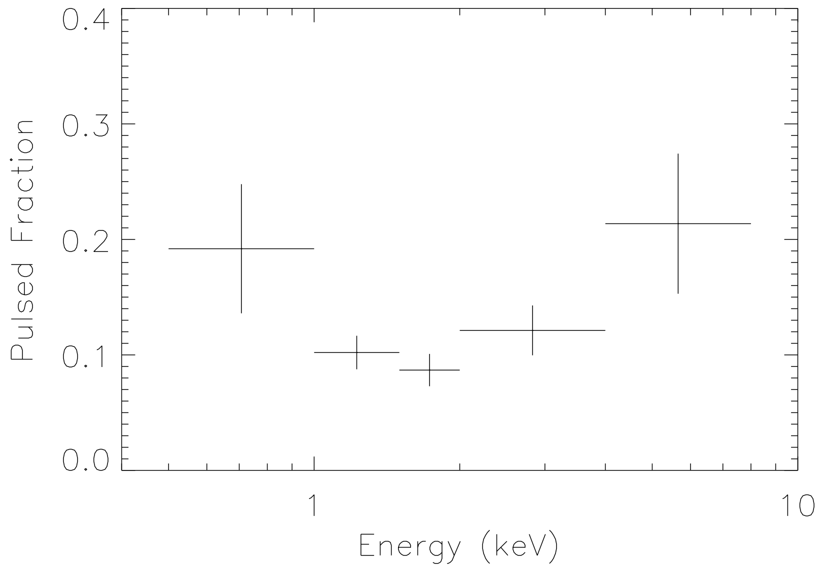

Figure 2. Pulsed fraction as a function of energy, defined as $(F_{max} - F_{min})/(F_{max} + F_{min})$, where F_{max} and F_{min} are the maximum and minimum values of the observed photon flux. An energy-independent pulsed fraction is excluded at the 1.7σ level.

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